

Unexpected vertical current sheets in the magnetotail associated with northward IMF

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Received 27 November 2002; accepted 5 March 2004

Abstract

Fast magnetic field polarity changes detected in the quiet magnetotail by a spacecraft are usually attributed to thin cross-tail current sheet crossings. On September 14, 2001, Cluster registered several such events. However the IMF was northward for the previous 24 h and the formation of a thin current sheet was very unlikely. The multi-point analysis revealed that these sheets were almost vertically oriented, had strong shear and vanishing normal magnetic components and therefore should be interpreted as boundaries between two independent magnetic field domains (flux tubes), rather than crossings of the main cross-tail current sheet. We suggest that such anomalous configuration might form in the course of high-latitude reconnection of geomagnetic lobe and interplanetary field lines when IMF is northward.

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Keywords: Magnetotail; Vertical current sheets; Northward IMF

1. Introduction

Since the first Dungey model (Dungey, 1961) it is widely accepted that the dynamics of the Earth's magnetosphere is primarily determined by IMF reconnection with antiparallel geomagnetic field. When the IMF is southward, it merges with geomagnetic field lines on the day-side and new open field lines are added to the tail lobes, shaping the thin cross-tail current sheet with small normal component B_z . (Hereafter GSM frame of reference is used everywhere.) This sheet might have a thickness of a fraction of the Earth radius and be crossed by a spacecraft in ~ 100 s due to flapping motion with several tens km/s speed (Sergeev et al., 1988). Later excessive field lines return from the magnetotail to the

day-side during substorms (e.g., Nishida, 2000). When IMF $|B_y| > |B_z|$ (even if $B_z > 0$) the day-side reconnection still continues, but in a skewed configuration and with less efficiency (Nishida et al., 1998).

When IMF B_z is positive and larger than IMF $|B_y|$, it is antiparallel now to open geomagnetic field lines poleward of the cusps (e.g., Maezawa, 1976). Here the reconnection occurs independently in two hemispheres and is affected by IMF B_x and by the dipole tilt (season), which modify the angle between the IMF and the geomagnetic field. When the IMF line is reconnected in one hemisphere, one new IMF line and one open field line form. The other end of the latter is convected past the opposite polar magnetosphere, where it has chances to reconnect with another (antiparallel) open line (Crooker, 1992). The result of such re-reconnection is the closed field line carrying the magnetosheath plasma, which is added to the flank boundary layer and eventually convected inside

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the night-side magnetosphere (Le et al., 1996; Tanaka, 1999). Since field lines are removed from the lobe and added to the plasma sheet, the plasma sheet expands in the vertical direction, being filled by cold dense plasmas and attaining a more spherical magnetic field configuration with a large local B_z (Huang et al., 1989; Nishida, 2000).

The four Cluster spacecraft offer a unique possibility to determine spatial structure of the magnetotail plasma sheet. On September 14, 2001, amidst the plasma sheet with large B_z and after almost 24 h of continuous northward IMF. Cluster detected five magnetic field (mostly B_x) sharp enough polarity reversals. Since the thin cross-tail current sheet is not expected to exist under such conditions, one has to suppose some internal irregularity in the plasma sheet magnetic structure or unrealistically high relative velocity. We suggest the scenario of formation of such a nonuniformity based on the specifics of the reconnection process of geomagnetic field with northward IMF.

2. General description of the magnetospheric state

During September 14, 2001 a rather rare case of almost 24-h long continuous northward IMF orientation

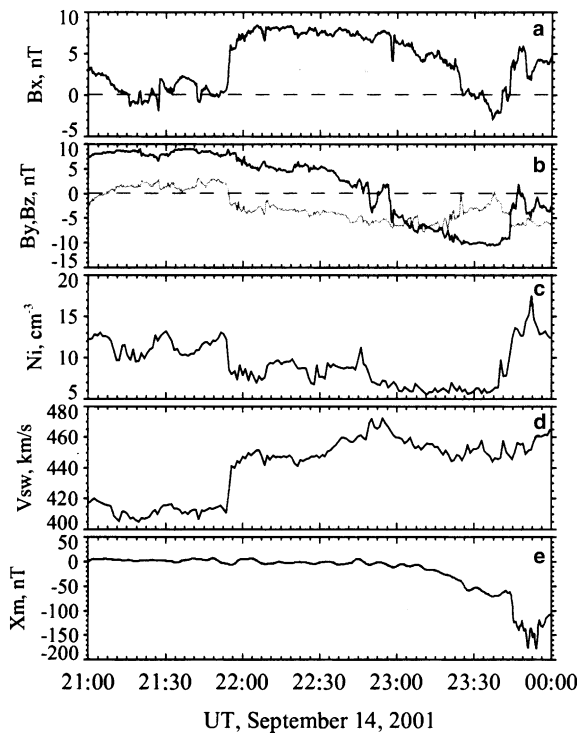


Fig. 1. ACE solar wind and IMF data for the last 3 h of September 14, 2001, shifted to allow for the propagation time of the solar wind flow to Earth. From top to bottom: (a) IMF B_x , (b) IMF B_y (shaded) and B_z (solid), (c) ion density, (d) solar wind flow velocity. At the bottom: (e) geomagnetic field X component variations at MUO (68.03°, 23.54°).

occurred. Here we will concentrate on the interval 21:00–24:00 UT (Fig. 1), where Cluster measurements were available. The IMF B_z was stagnant northward at ~ 10 nT for 21–22 UT, then gradually decreased to zero at 23:00, starting a 45-min interval of southward orientation. IMF B_y was smaller than B_z during the northward IMF interval, while B_x was first small, then, after 22:00, it was large positive. The ground magnetograms from a number of magnetic observatories distributed worldwide (Fig. 1(e)) are consistent with southward IMF profile: the geomagnetic field was quiet until 23:00, when the convection bay associated with the southward IMF (substorm growth phase) developed at auroral latitudes. According to global aurorae observations on-board the IMAGE spacecraft (not shown here) several substorm onsets commenced at 23:30–24:00 UT at different MLT.

The Cluster-1 magnetic data (Balogh et al., 2001) and spacecraft coordinates for the interval of interest are presented in Fig. 2. Cluster was located near its apogee, in the premidnight sector of the plasma sheet. The spacecraft magnetic footpoint (computed with the T96 model with appropriate IMF and D_{st}) was just northward from Iceland (for 23:00 UT). The spacecraft was also 1.5–0.7 R_E above the model neutral sheet position (Fairfield, 1980). The magnetic field configuration was characterized by a strong normal magnetic field component $B_z \sim 5$ –10 nT, while typical magnitude of B_x was 20 nT and $|B_y|$ was within 5 nT. The T96 model prediction for B_z at this location is 3 nT. The southward IMF-associated plasma sheet stretching revealed itself in the Cluster data only after 23:15 UT when the magnetic field component normal to the equatorial plane B_z , became small ~ 2 –3 nT. Signatures of the substorm expansion

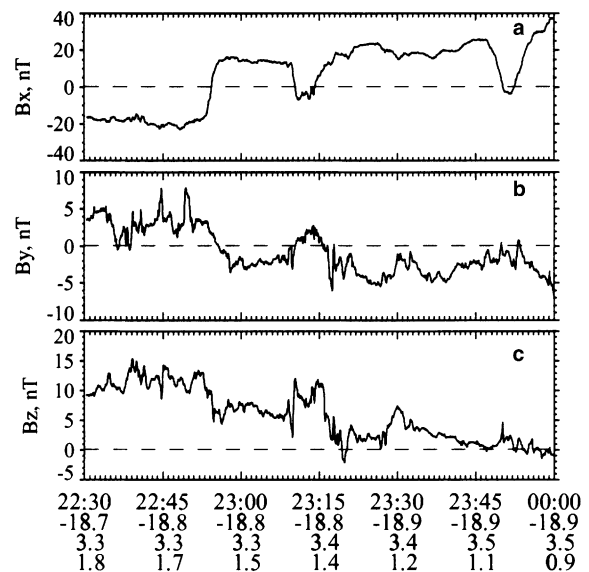


Fig. 2. Overview of Cluster-1 data: (a–c) GSM magnetic field. Below are GSM spacecraft coordinates in R_E .

were detected only after 00:00 UT of September 15th (not shown here).

3. Current sheets structure

The fast magnetic field B_x polarity reversals (current sheet encounters) were detected by the Cluster spacecraft at 22:54, 23:10, 23:14, 23:50 and 23:54 UT (hereafter crossings 1–5, Fig. 2). Table 1 contains summary characteristics of all crossings, determined with the help of the 4-point measurements as it is explained below.

The first crossing occurred at 22:54 UT as a clear smooth 100-s long change from negative to positive B_x (Fig. 3). The spatial orientation of a planar boundary with a finite thickness can be determined comparing instantaneous magnetic measurements of four spacecraft and assuming that the magnetic gradient inside a boundary is constant. Alternatively, to calculate the normal and the propagation velocity along it, one can use time delays between measurements with the same magnetic field values. In our case both methods resulted in almost the same directions, and Table 1 contains the time delay determined normal N and velocity V_n . Cluster actually crossed here almost vertical current sheet: the angle between the normal and Y GSM axis δ_{NY} was 11° .

Another independent characteristic of a magnetic field reversal is direction of the maximal variance L . In a planar sheet it should be orthogonal to the normal. Here the angle δ_{NL} is less than 2° apart from 90° . For each magnetic field reversal we established the local boundary coordinate system with the L axis parallel to direction of maximal variance, the N axis perpendicular to L and closest to the estimated sheet normal, the M axis in the plane of current sheet and in accordance with the right-hand geometry.

The magnetic field components in this reference frame reveal intrinsic features of the current sheet (Fig. 3(e)–(g)). It had the B_l profile close to the Harris shape with nonequal magnetic field on both sides. The shear component B_m was large, while the normal component B_n fluctuated around zero. Therefore, magnetic field lines do not cross this current's sheet. Such sheared sheets are typical at the Earth's magnetopause. The characteristic width Δ of 1226 km was estimated by a fit of the Harris function to the magnetic field profile.

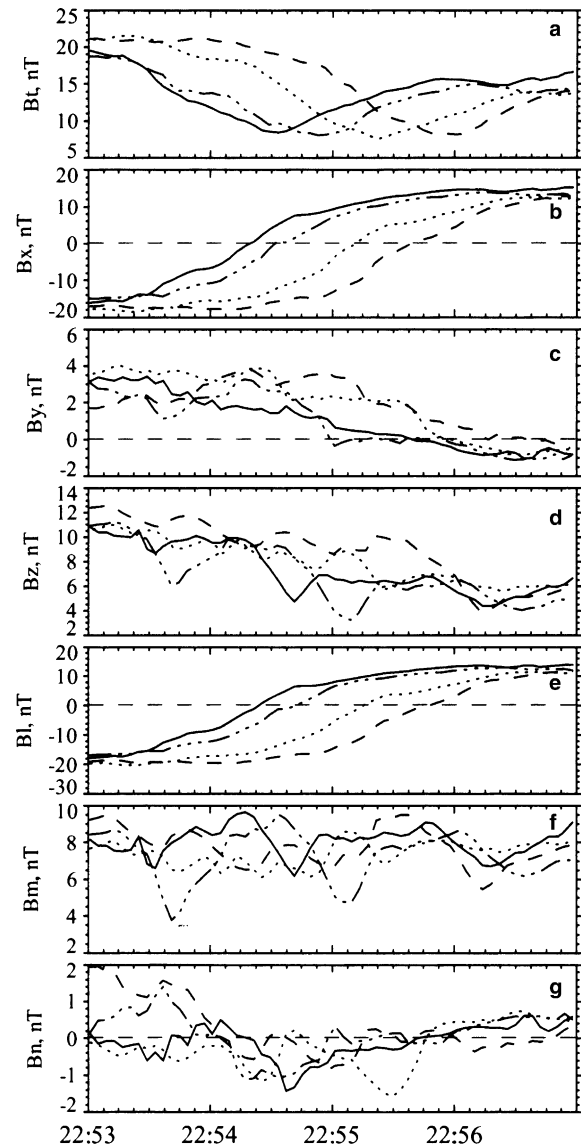


Fig. 3. Cluster crossing 1. From top to bottom: (a) total magnetic field, (b–d) GSM magnetic field, (e–g) boundary frame magnetic field. Cluster-1 (solid), Cluster-2 (dashed), Cluster-3 (dotted), Cluster-4 (dash-dot).

The second and the third crossings were similar in their characteristics, but the magnetic field was rather nonsymmetric (negative B_x was noticeably smaller) and the estimates of the sheet thickness varied substantially. The crossings 4 and 5 happened during the late

Table 1
Parameters of current sheet crossings

#	UT	N	δ_{NY} ($^\circ$)	L	δ_{NL} ($^\circ$)	V_n (km/s)	Δ (km)
1	22:54	−0.07, −0.98, 0.17	11.5	0.98, −0.12, −0.16	88.9	−22.9	1226 ± 43
2	23:10	−0.11, −0.99, 0.03	8.1	0.98, −0.14, −0.12	89.9	25.1	404 ± 64
3	23:15	−0.14, −0.97, 0.18	14.1	0.98, −0.14, −0.12	89.9	−18.2	4137 ± 965
4	23:50	0.20, 0.26, 0.94	19.9^a	0.99, −0.02, −0.07	82.7	21.7	2322 ± 968
5	23:54	0.19, −0.67, 0.72	47.9^a	0.99, −0.02, −0.06	80.9	−23.2	$−5500 \pm 4000$

^a Here angle δ_{NZ} .

growth phase. The magnetic field configuration was more stretched (B_z was small enough) and the orientation of the current sheet plane was closer to horizontal. Reliable determination of the sheet width was difficult because only one half of the sheet was actually crossed.

4. Discussion

Observations of Cluster at $-20 R_E$ downtail near the midnight helped to reconstruct the large-scale structure of the plasma sheet during steady northward IMF (IMF $|B_y| < B_z$). With such an IMF direction, the lobe field lines erode and the plasma sheet (and auroral oval) is expanded to high latitudes due to addition of the reconnected field lines via the LLBL.

In support to this scheme, it was found, that the plasma sheet is filled with magnetic field lines, having a high normal component (5–10 nT) near the equatorial plane. This value is larger than the dipolar field and the T96 model estimates (~ 1 –5 nT) for these downtail distances. Therefore it might be not appropriate to use this model for quantitative purposes in the magnetotail during intervals of strongly northward IMF. Because of data coverage and orbital limitations, it was impossible to determine the high-latitude extent of the plasma sheet. However, the sheet thickness was at least several Earth radii, since plasma was detected a couple radii higher and lower than the nominal field reversal plane (Fairfield, 1980).

In a thick plasma sheet with a dipolar magnetic field or a large normal magnetic field component, the cross-tail current sheet, a relatively thin planar layer, in which the magnetic field direction is reversed, does not exist. Therefore, one should not expect to detect fast field direction changes by a spacecraft moving across such a plasma sheet, unless the relative velocity is unreasonably high. However, as it was demonstrated in this investigation, magnetic field reversals, which otherwise would be interpreted as thin current sheet crossings, are occasionally observed even in a thick plasma sheet configuration. These current sheet are rather unusual for the magnetotail: they are almost vertically aligned, have strong shear and vanishing normal magnetic field components. Magnetic field lines do not actually cross such current sheet and it could be understood also as a boundary between two adjacent magnetic field configuration (tangential discontinuity). Nevertheless, the reversal zones do contain electric current, which self-consistently supports the field direction changes.

To explain these observation, we suggest that the observed field reversals are vertical boundaries between neighboring in Y magnetic flux tubes, some of which are asymmetric with respect to equatorial plane due to a significant vertical (poleward) shift of their tail-most parts. Because of such, e.g., northward shift, at some Z levels in the northern hemisphere, Earthward directed

“normal” field lines will neighbor tailward directed parts of shifted field lines (nominally from the southern hemisphere). In the boundary frame of reference the large B_z magnetic field component will play the role of a shear component. Since field tubes lie in almost parallel planes, the magnetic field component across the boundary should be close to zero in accordance with our observations. According to velocity analysis the anomaly field tubes flap in Y direction with speeds of some tens km/s, which are typical for such type of a motion (Sergeev et al., 1988).

The desired field line asymmetry with respect to the equatorial plane might be naturally formed during the high-latitude reconnection process. Under northward IMF, the reconnection is privileged in one of the lobes (as determined by a season and IMF B_x). The location and time of (later) reconnection in the other lobe, which is required to produce the closed field line, are affected by peculiarities of downtail magnetosheath convection in each concrete case. After such second re-reconnection, the newly formed closed field line has a kink (or tail-most part of a field line) significantly above (or below) the equatorial plane. This kink should evolve (and relax) while the field line is convected further. However, on a speculative basis, some kinks might remain away from the equatorial plane, while the corresponding field line is already located deep inside the tail. The general poleward expansion of the plasma sheet field lines caused by the lobe erosion, facilitates preservation of such nonsymmetric configuration.

With the IMF southward turning after a period of northward IMF, additional field lines are added to the lobe and exert pressure on the plasma sheet, forming the stretched magnetic configuration and, probably, gradually pressing shifted field lines equatorward to the nominal position. The sequence of five crossings observed right after the start of a growth phase on September 14, 2001, with characteristics evolving from vertical boundary of almost antiparallel fields to more oblique partial reversals is consistent with such a scenario if the spacecraft detected the same evolving object rather than several different ones.

The profile of the first Cluster reversal can be fitted by a modified nonsymmetric Harris distribution with a high degree of confidence. Its scale parameter (half thickness) was ~ 1200 km. For the next crossings Harris fits were not so accurate, resulting in significant scatter of the scale from 400 to 4000 km. However, the thickness of such current sheet should be determined by relative instant motions of flux tubes and is not necessarily stable.

The magnetotail configuration and global (reverse) convection under strictly northward IMF are, in some sense, opposite to the dynamics of the open magnetosphere under southward IMF. However, these northward IMF cases are not necessarily the intervals of magnetic quiescence (with low indices K_p , or A_p). For

our events K_p , was 1+ and 3– due to rather dense and variable solar wind. On the other hand, the magnetosphere might be formally quiescent but still open, when the IMF is weak and azimuthal. In such a case, convection is principally the same as during active periods, though substorms are weaker (Nishida et al., 1998; Petrukovich et al., 2000).

Acknowledgements

We are grateful to ACE, IMAGE spacecraft teams for their data available online and to WDC and CDA-Web data centers. We thank the Institutes who maintain the IMAGE magnetometer array. A.A.P. acknowledge the Russian/Austrian Academy exchange program and hospitality of IWF, Graz. The work by K.H.G. was financially supported by the German Ministerium für Bildung und Wissenschaft and the German Zentrum für Luft- und Raumfahrt under contract 50 OC 0103.

References

- Balogh, A., Carr, C.M., Acuna, M.H., et al. The Cluster magnetic field investigation: overview of in-flight performance and initial results. *Ann. Geophys.* 19, 1207–1217, 2001.
- Crooker, N.U. Reverse convection. *J. Geophys. Res.* 97, 19363–19372, 1992.
- Dungey, J.W. Interplanetary magnetic field and the auroral zones. *Phys. Rev. Lett.* 6, 47–48, 1961.
- Fairfield, D.H. A statistical determination of the shape and position of the geomagnetic neutral sheet. *J. Geophys. Res.* 85, 775–780, 1980.
- Huang, G.Y., Craven, J.D., Frank, L.A. Simultaneous observations of theta-aurora and associated magnetotail plasmas. *J. Geophys. Res.* 94, 10137–10143, 1989.
- Le, G., Russell, C.T., Gosling, J.T., Thomsen, M.F. ISEE observations of the low-latitude boundary layer for northward interplanetary magnetic field: Implications for cusp reconnection. *J. Geophys. Res.* 101, 27239–27249, 1996.
- Maezawa, K. Magnetic convection induced by the positive and negative z components of the interplanetary magnetic field: quantitative analysis using polar cap magnetic records. *J. Geophys. Res.* 81, 2289–2303, 1976.
- Nishida, A. The Earth's dynamic magnetotail. *Space Sci. Rev.* 91, 507–577, 2000.
- Nishida, A., Mukai, T., Yamamoto, T., Kokubun, S., Maezawa, K. A unified model of the magnetotail convection in geomagnetically quiet and active times. *J. Geophys. Res.* 103, 1409–4418, 1998.
- Petrukovich, A.A., Baumjohann, W., Nakamura, R., Mukai, T., Troshichev, O.A. Small substorms: solar wind input and magnetotail dynamics. *J. Geophys. Res.* 105, 21109–21118, 2000.
- Sergeev, V.A., Angelopoulos, V., Carlson, C., Sutcliffe, P. Current sheet measurements within a flapping plasma sheet. *J. Geophys. Res.* 103, 9177–9187, 1988.
- Tanaka, T. Configuration of the magnetosphere-ionosphere convection system under northward IMF conditions with nonzero IMF B_y . *J. Geophys. Res.* 104, 14683–14690, 1999.